

The EOS Aqua/Aura Experience: Lessons Learned on Design, Integration, and Test of Earth-Observing Satellites

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NASA and NOAA earth observing satellite programs are flying a number of sophisticated scientific instruments which collect data on many phenomena and parameters of the earth's environment. The NASA Earth Observing System (EOS) Program originated the EOS Common Bus approach, which featured two spacecraft (Aqua and Aura) of virtually identical design but with completely different instruments. Significant savings were obtained by the Common Bus approach and these lessons learned are presented as information for future programs requiring multiple busses for new diversified instruments with increased capabilities for acquiring earth environmental data volume, accuracy, and type.

I. Introduction

A major part of the NASA/GSFC EOS Program is the scientific instruments carried on the Terra, Aqua, and Aura satellites. Terra, launched in 1999, was built by Lockheed and launched on an Atlas; subsequently, the specification for Aqua and Aura was modified to require launch on a medium EELV. This change required reducing the size of Aqua and Aura and placed a premium on efficiency in carrying a full complement of twelve scientific instruments (eight on Aqua, four on Aura). Terra, Aqua, and Aura were originally known as EOS AM, EOS PM, and EOS Chemistry, because Terra and Aqua crossed the equator in the morning and afternoon (thus, AM and PM) and Chemistry's instrument complement concentrated on ozone measurement, atmospheric chemical reactions, and atmospheric constituents. With an emphasis on cost, the program objective for Aqua and Aura was to design and produce a Common Bus, or a spacecraft common to both programs but with the capability to host either instrument suite, and to accommodate changes in instrument complement and characteristics well into the program. The Common Bus design proved capable of meeting these objectives, and the advantages of the commonality were proven in cost and schedule reductions for the second spacecraft. Extensive use of common structure, subsystem design, components (including common equipment buys) and test procedures and documentation showed that a common spacecraft could host widely differing instrument complements if sufficient design flexibility is built in initially.

II. The Aqua and Aura Missions

As suggested by the satellite names, Aqua is designed to monitor the Earth's water cycle, and Aura's instruments collect data on atmospheric chemistry. Aqua was launched in May 2002 and is operating successfully in a sun-synchronous orbit of 705 km. altitude. Aura was launched in June 2004 and is completing initial on-orbit checkout prior to full operation of the scientific instruments. Aqua and Aura are flying at the same altitude and inclination, and will be orbiting at the front and trailing positions at either end of a procession of spacecraft called the "A train": between Aqua and Aura will be several smaller satellites with additional environmental data collection capabilities. Aqua and Aura are controlled from the ground to maintain relative position so that correlated measurements (geographically) can be made for both instrument suites and from the other instruments on board the smaller satellites. Aura is positioned such that its limb scanning instruments search a portion of the atmosphere also observed at the same time by Aqua's nadir pointing instruments. The constellation completes 14.4 orbits each day, and a repeating ground track every 16 days. Equator crossing is controlled to 15 minutes so that consistent lighting conditions obtain for the observations. (I think a word is missing in this sentence)

Commonality in spacecraft bus design was aided by the mission requirements to fly both spacecraft (as well as the other smaller spacecraft in the A train) in the same altitude and inclination orbits, thereby setting up the same environmental requirements for both missions. However, the instrument complements were entirely different, given the mission objectives for water-cycle evaluation for Aqua and for atmospheric chemistry for Aura. Therefore, the

instrument accommodations were unique to each spacecraft: the common bus design objective was to retain maximum commonality in the bus design with maximum flexibility in instrument accommodation.

A brief review of the instrument suites will introduce the EOS mission objectives and indicate the degree of mission-unique instrument accommodations required. Aqua and Aura fly separated by about 15 minutes in orbits covering virtually the same ground tracks in near-polar orbits. Worldwide coverage of the environmental parameters being measured is obtained around the clock. The designed lifetime of the spacecraft is six years, and in conjunction with other spacecraft (plus ground and aircraft observations) will yield an unprecedented global view of earth's climate and atmospheric chemistry changes.

Aqua carries eight instruments of six types totaling 1082 kg, Aura carries four somewhat larger instruments with a payload weight of 1115 kg. The spacecraft allocated 1200 kg. for both configurations.

The Aqua instruments are:

AMSR-E – Advanced Microwave Scanning Radiometer-EOS, developed by the National Space Development Agency of Japan

MODIS – Moderate Resolution Imaging Spectroradiometer, developed by Raytheon

AMSU – Advanced Microwave Sounding Unit, developed by Aerojet (2 units carried)

AIRS – Atmospheric Infrared Sounder, developed by BAE Systems

HSB – Humidity Sounder for Brazil, developed by Matra Marconi Space

CERES – Clouds and the Earth's Radiant Energy System, developed by TRW

Aura instruments are:

HIRDLS – High Resolution Dynamics Limb Sounder, developed by the University of Colorado and Oxford University, together with Lockheed

MLS – Microwave Limb Sounder, developed by JPL

OMI – Ozone Monitoring Instrument, developed by Dutch Space

TES – Tropospheric Emission Spectrometer, developed by JPL

Figure 1 is an illustration of the two EOS satellites. The instrument payloads are carried on the earth-facing deck of each satellite, as shown in the illustrations. The large dish antenna on Aqua is the rotating antenna of the AMSR-E instrument; the two instruments shown on the aft end of the satellite are dual CERES instruments. The Aura illustration shows the scanning MLS antenna and components on the front end of the spacecraft, followed (moving aft) by HIRDLS, TES, and then the three smaller units that make up the OMI instrument. One difference in the spacecraft is that the X-band antenna, used to send the science data to the ground, is fixed on Aura but, because of space limitations (resulting from the CERES requirements) had to be placed on a deployable boom on Aqua.

Instrument accommodations had to be flexible enough to handle some design uncertainties, particularly for the Aura instruments that were not as well defined as Aqua's.

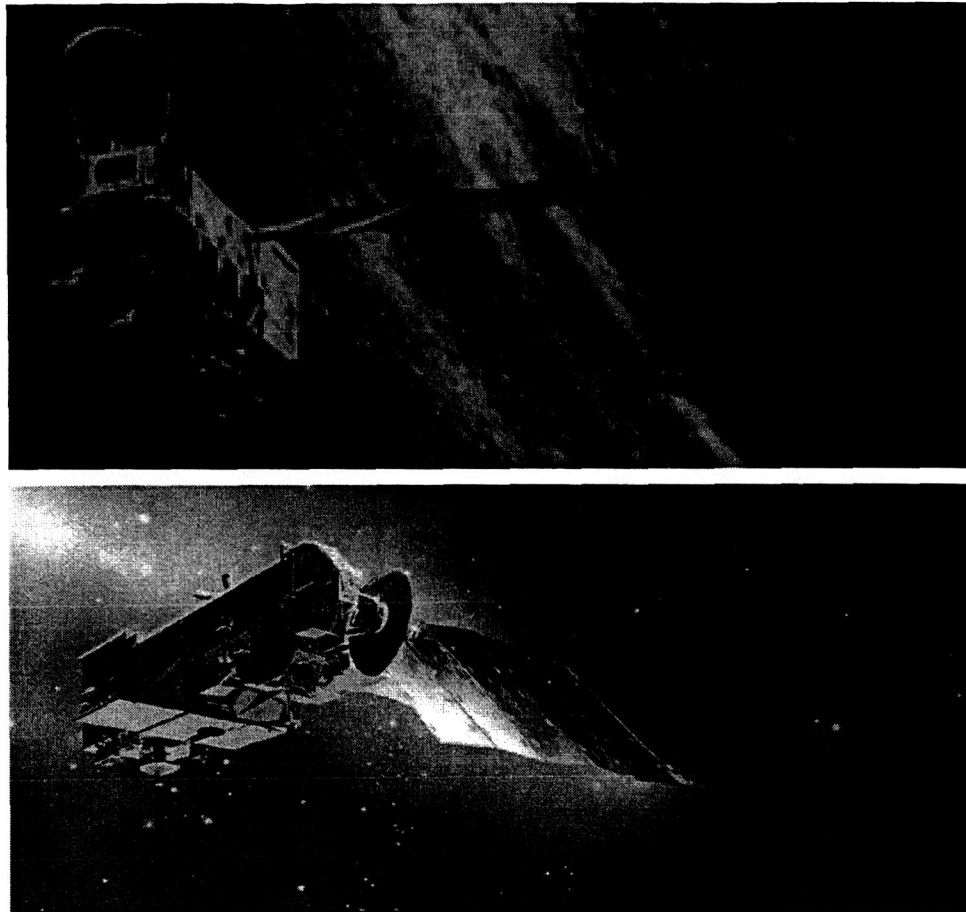


Figure 1. Aqua (top) and Aura satellite illustrations

Although both instrument suites are environmental sensing intensive, there are very significant differences between them in terms of instrument accommodation. For example, Aqua's instruments require three separate voltages in the electrical power supply. Since Aura's instruments look at the Earth's limb (except for OMI) Aura has more stringent pointing control and knowledge requirements than Aqua (the limb is three times farther away than the nadir point). Since the final makeup of the instrument suite was not fully determined for Aura at the time of the contract award, flexibility within the total instrument weight and power allocation was required to accommodate possible changes, which did occur when OMI replaced an earlier ozone instrument midway through the program. The AMSR-E instrument, provided by Japan, was introduced to Aqua after initiation of the program, replacing another instrument of similar design, but required different interfaces. AMSR-E contains a large rotating antenna scanning the earth, and control of the momentum of this antenna presents issues to the spacecraft attitude control designers.

In summary, the spacecraft program was presented with two separate sets of instruments, similar in total weight and power, but quite different in measurement characteristics, voltage requirements, pointing requirements, and physical envelopes and mounting configuration. The challenge for the spacecraft designers was to retain nearly complete commonality between the spacecraft design while not compromising instrument accommodation. Since the NASA program offices running Aqua and Aura were independent (although both reporting to the same higher level office) both needed to be separately satisfied that the commonality philosophy did not sacrifice their individual instrument accommodations just for the sake of cost control at the observatory contractor.

Although the two instrument payload complements were quite different, some shared overall design specifications contributed to achieving a common design. Total payload weight was specified as 1200 kg. and the structure was designed, tested, and qualified to that level. The extra margin built-in through the 1200 kg. specification reduced concern about instrument weight growth during the program. Total payload power was specified as 1200 watts; since the electrical power system was modular (number of solar cells and battery cells could be varied as needed) larger power margins were not required. Aqua fell well under the 1200 watt specification, but Aura needed an increase to 1300 watts during the program as instrument power requirements grew during the program. The additional 100 watts were accommodated through the designed margins without change in the electrical subsystem (which remained identical to Aqua's).

III. The Objectives of a Common Bus Design

Commonality in bus design for space programs which feature multiple spacecraft but different payloads is a frequent objective but often difficult to achieve when program realities such as funding limitations and evolving requirements tend to push the program to greater specialization for each spacecraft. Funding realities usually prevent large expenditures in a short time period required to buy all parts and build all spacecraft at the same time; other issues such as personnel availability and facility limitations also limit the number of spacecraft that can be built in parallel. However, as Aqua and Aura showed, the payoffs in cost, schedule, and technical learning curves are strong enough to drive continued commitment to a common bus design. A major lesson learned in the EOS program was to maintain the common design even when well-intentioned recommendations for specialization were made. By keeping commonality at a high level, even at some sacrifice in optimization of each individual mission, costs and schedules could be maintained and 'requirements creep' issues could be suppressed.

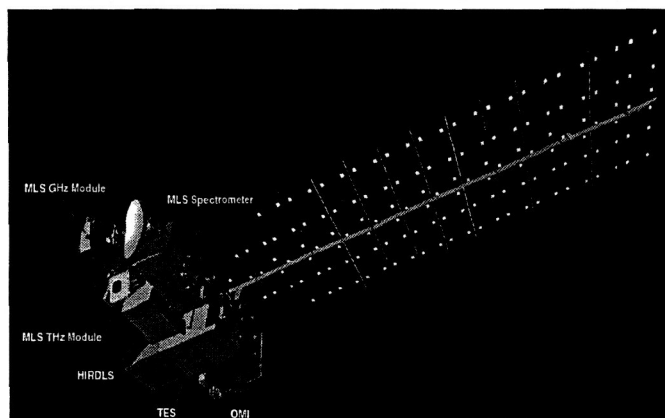


Figure 2. Aura spacecraft instrument complement

It was generally advantageous to retain commonality even in cases where changes might optimize performance for one or the other program, since the advantages of equipment interchangeability could be maintained. For example, the inertial reference unit had an option to provide a high rate link via an RS-422 bus to an instrument on Aura that required such a capability. Even though Aqua did not require this capability, the two IRU's were ordered and delivered with this option. When a subsequent gyro channel electronics failure required the removal of one IRU, the other could be substituted without interruptions in testing because it had the same features as its twin. Completely common subsystem designs resulting in interchangeable components proved valuable during the testing program when equipment problems developed requiring removal and replacement of spacecraft components.

The EOS program objectives concerning the development of a truly common bus for both missions then, were:

1. Reduce overall cost by achieving economies of scale in equipment acquisition, common design activity and drawings, and common use of supporting equipment, test documentation, and facilities.
2. Improve efficiency through the use of serial and parallel production using common documentation and procedures.
3. Increase the efficiency of the integration and test personnel by using identical procedures for both spacecraft, hence retaining the on the job training acquired on the first of the spacecraft
4. Make the program more flexible in terms of instrument accommodation by designing the spacecraft to accommodate different instruments via a 'kit', or instrument-specific set of mountings and interfaces without affecting the basic spacecraft design.

5. Make spacecraft components interchangeable between the spacecraft to provide reduced cost, sparing and rapid component replacement capability during I&T.
6. Reduce training time and scope for flight operations personnel by using common documentation and procedures for operating the spacecraft.
7. Obtain high levels of reusability for bus software not unique to instrument support.

It was anticipated that there would be some impacts to each mission by making commonality a cornerstone of the programs. For example, the power subsystem for Aqua could have been slightly smaller than Aqua's, and Aqua's attitude control subsystem slightly less capable than Aura's. Primary structure design could have been optimized for each mission with a small reduction in structural weight. Changes of this type would have led to different drawings, different subsystem specifications, and spacecraft-unique documentation and testing. The advantages of commonality far outweighed minor non-optimum design issues.

IV. Commonality Guidelines and Lessons Learned

The approach emphasized a completely common spacecraft bus that could envelope the instrument support requirements for an instrument suite still subject to design modifications. In particular, the Aura instruments were still in a state of design completion at the time of the award of the bus contract and the start of bus design. The Aqua instruments were better defined and in the start of production, but still subject to weight and power growth risk. Neither mission's instrument set was immune from change in the complement due to factors outside the control of the program office. In fact, during the program the scanning radiometer on Aqua was replaced by AMSR-E, a similar instrument, and a nominal ozone instrument slot on Aura was not filled by the OMI instrument until well into the program. Hence, a lesson of the commonality theme was to make the spacecraft adaptable to instrument requirement and configuration changes without impact to the basic bus configuration.

The design approach was to provide a clear upper deck to maximize instrument field of view (all the instruments required a clear view of the Earth or its limb). Since the exact instrument weights were not known initially, an allocation with significant room for growth was assigned to both Aqua and Aura – 1200 kilograms – and the common design was capable of handling the loads associated with this high-margin value. A structural prototype was produced and load tested with the full 1200 kg. payload in the form of mass models of the instruments. The structure was qualified, through load and dynamics testing, with this payload. At this maximum payload capability, the total design weight of the entire vehicle was within the lift capability of the Delta II launcher; as long as the launcher lift capability is met, the cost of adding weight to the structure to accommodate loads with a large margin is very small, and protects against redesign (and requalification) later if the structure needs to be strengthened. The instruments eventually showed relatively small weight growth, but the margin provided protected the program against later cost increases.

The instrument power requirements also tend to grow during the evolution of the instruments. Similar to the tenet of enveloping both mission weight requirements with margin, the electrical power subsystem was designed to provide 1200 watts to either mission's instrument complement. Instrument power requirements did grow somewhat, notably due to accommodation of thermal issues involving heater power during safe mode operations, but the margin available met the growth needs. Aura power estimates were less specific than Aqua's initially, due to the new design status of the instruments, and the Aura instrument power requirement was subsequently raised to 1300 watts with no change in the design. The first lesson applied was to envelope multiple mission weight and power requirements in the initial design, retaining launch vehicle life margin, to prevent requirements creep from forcing incremental changes in structural and electrical power subsystems.

Given that the primary structure was qualified for maximum mission weight, the commonality philosophy sought to eliminate any changes to the structure resulting from instrument mechanical mounting requirements. Therefore, the instrument support elements of the mechanical subsystem were designed as a 'kit', or special purpose secondary structure mounting to the primary structure. The secondary structure mechanical mounting carried the kinematic mounts, or flexure supports, which provides three point mounting of the instruments that do not shift in alignment over thermal changes. The kinematic mounts could not be designed until the instrument dynamics and mounting requirements were known, so placing them on the secondary structure kept the primary structure free of dependence on the specifics of instrument configuration. This approach adds a small amount of weight via the secondary structure, but more than pays off by keeping the much more costly primary structure free of changes throughout the program. Figure 3 shows a photograph of the primary structure before final assembly and instrument addition, showing the graphite epoxy compartmentalized design.

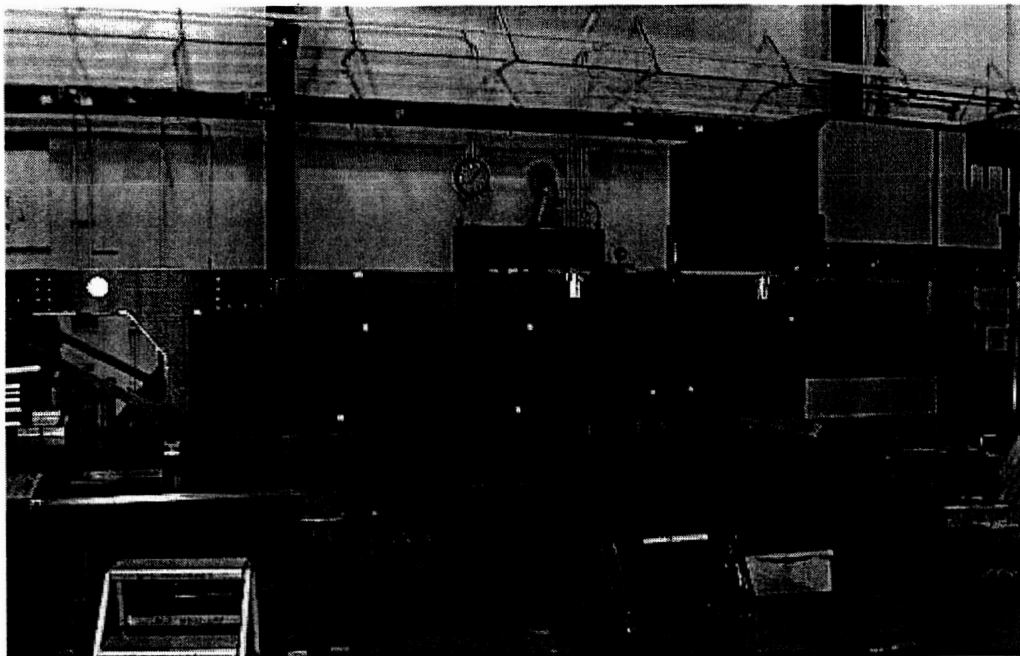


Figure 3 – Common Bus Primary Structure

A lesson learned in software design was to enforce commonality in bus software, restricting software changes between missions to instrument support portions only, and isolating those modules from the unchanged software. This obviously reduced the non-recurring design and development cost for the software, but had a real payoff in the decision to not retest unchanged code. Extensive testing of flight software, while necessary to ensure mission success, is expensive, and the program was successful in convincing software quality management that unchanged modules need not be retested. Software engineers were careful to verify that the changes in instrument support software did not ripple into the spacecraft software, and the end to end testing of the spacecraft final preship testing verified correct software operation. The result of enforcing software commonality, at the small expense of non-optimization of the code for each mission, was that the Aura software costs were less than 20% of Aqua's.

The theme of commonality was carried into the design of the spacecraft subsystems for attitude control, electrical power, thermal control, communication, and command and data handling subsystems. By making these subsystems entirely common between spacecraft, a common parts and component buy was possible, reducing cost significantly and eliminating non-recurring costs for the second spacecraft. Commonality in these areas permitted the team to use subsystem specifications identical for both spacecraft, and identical planning and documentation for testing and verification.

Some amount of compromise to each mission results from completely common spacecraft subsystems, but all of the scientific instrument requirements continued to be met. For example, the instrument data rates for Aqua were about 25% higher than Aura's; therefore, the design of the Solid State Recorder (SSR) was modular, with capacity a function of the number of memory modules installed, but the formatting portion was identical. The unit configuration was identical, and in place of the Aqua memory boards for the mission's larger memory requirements, the Aura unit flew empty boards so that the dynamics testing and qualification could be applied to both units. The SSR common design proved valuable when one unit was required to substitute for the other during the testing, and the memory capacity of either SSR easily adjusted by installing or removing memory boards.

The attitude control system design was set by the somewhat tighter pointing requirements of Aura, but both spacecraft retained the common design; the only change driven by the Aura requirements was the use of a rotary joint damper at the connection of the solar array and the drive motor, to suppress the effects of solar array motion on the spacecraft attitude. Although Aqua could have met its requirements without the unit, it was installed on Aqua as well, providing more margin in pointing and yielding the added advantage of two years of on-orbit performance experience in evaluating the predicted performance of Aura.

After completion of the basic structures for both spacecraft, and the installation of the common spacecraft equipment, the integration and test phases commenced; the eight and four (respectively for Aqua and Aura) scientific instruments were installed and full-up observatory testing began. At this point it might be assumed that the spacecraft were different and now required separate testing and procedures. However, since the instruments were communicating through high-speed data busses, and the formats of the output scientific data were the same for both spacecraft, the observatory testing followed the same sequence for both. The commonality of the spacecraft equipment meant that any tests involving spacecraft component testing, or interface with the instruments, could use the same procedures, so that the two programs shared the same test documentation. Instrument tests were unique to the instrument, but most of the tests involving the instruments specifically were functional in nature; performance testing had been completed at the instrument makers prior to delivery.

The I&T phase for the assembled observatory, which includes extensive environmental testing (vibration, shock, thermal vacuum) is a significant contributor to the program's cost and schedule. Although the common design approach allowed common test procedures and documentation to be used, and improved the I&T crew familiarity with integration and test for Aura, a further lesson learned was the benefit of a common design to the scope of the test program. Many of the I&T tests involve the exercise of the spacecraft equipment verifying connectivity and performance within the spacecraft. As part of NGST's Six Sigma process improvement program, we examined the planned test program in detail to identify testing which was aimed at qualification level objectives, rather than acceptance level. Qualification level testing shows that a particular design meets requirements, and acceptance level testing shows that a tested component (or subsystem) is representative of that design. Much of the testing on Aqua, as the first unit of a series, has qualification level characteristics. However, since Aura had the same design as Aqua at the bus level (and the same software) the Six Sigma team determined that tests on Aqua that demonstrated design correspondence to requirements could be eliminated on Aura. Although the initial benefits of commonality in I&T were reached by using common documentation and procedures, shortening the test program provided even greater improvements. The lesson learned was that testing for a common design should consider the overall joint test program whereby testing is viewed as a means of verifying the common design, and need not be identical for both spacecraft.

The benefits of the emphasis on a common bus design can be seen with the metrics developed to compare Aura with the first spacecraft, Aqua. Figures 4 and 5 compare Aqua and Aura in metrics including cost and time spans for various intervals such as start of I&T to thermal vacuum test preparation, and the delivery of the last instrument to launch (the instrument integration and observatory test phase). The number of test discrepancy reports is greatly reduced for Aura, indicating a strong learning curve during observatory testing even with different instrument complements.

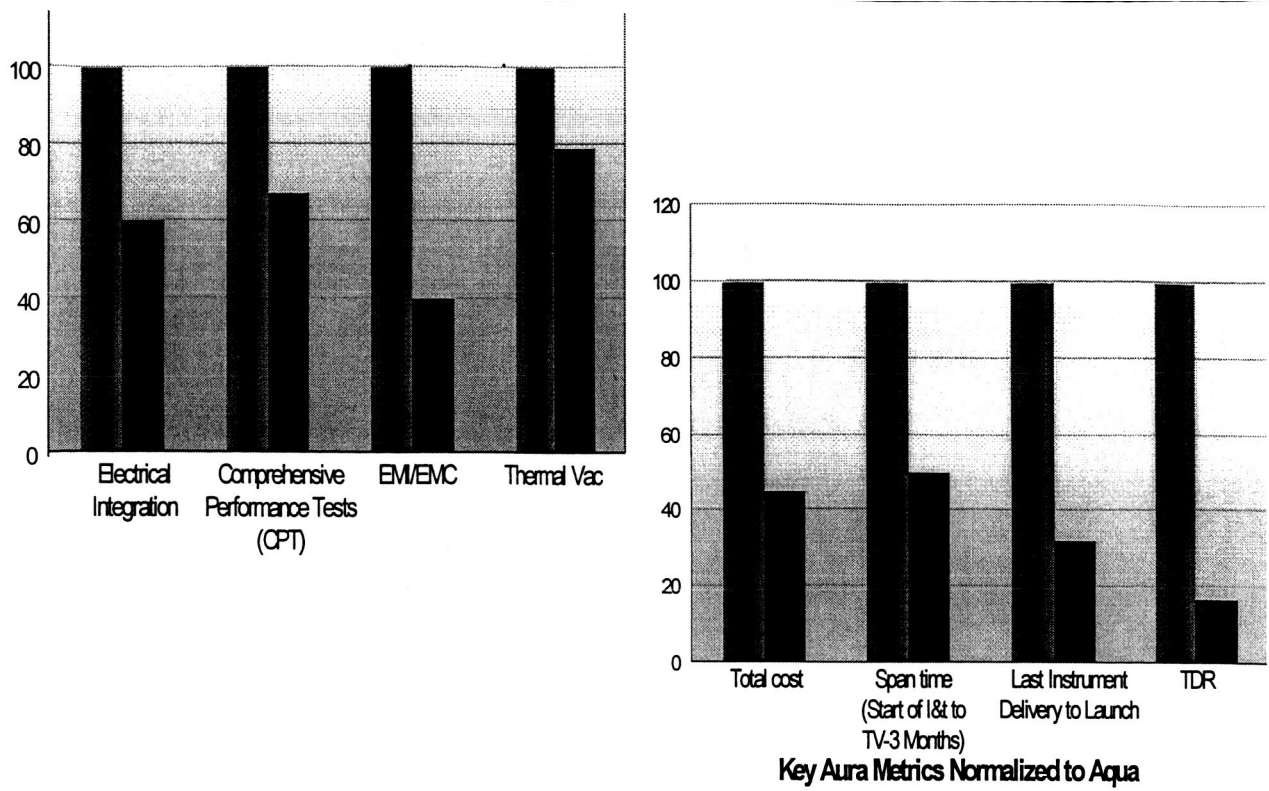


Figure 4. Aqua and Aura Metrics in I&T Reflect Benefits of the Common Bus Approach